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Temperatures and Non-ideal Expansion in Ultrarelativistic Nucleus-Nucleus Collisions

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Abstract

The hadronic phase space distributions calculated with the transport model RQMD for central S(200 AGeV) on S and Pb(160 AGeV) on Pb collisions are analyzed to study the deviations from ideal hydrodynamical evolution. After the preequilibrium stage, which lasts for approximately 4 (2) fm/c in Pb+Pb (S+S) the source stays in approximate kinetic equilibrium for about 2 fm/c at a temperature close to 140 MeV. The interactions of mesons last until around 14 (5) fm/c during which time strong transverse flow is generated. The interactions in the hadronic resonance gas are not sufficiently strong to maintain ideal fluid expansion. While pions acquire average transverse fluid velocities around 0.47-0.58 c, heavier particles like protons and kaons cannot keep up with the pionic fluid, since their average velocities are smaller by about 20 to 30 %. Although kinetic equilibrium breaks down in the final dilute stage of AA collisions, the system resembles a thermal system at a temperature of 130 MeV, if the free streaming of hadrons after freeze-out is suppressed. This freeze-out temperature is consistent with estimates based on mean free paths and expansion rates in a thermal fireball but lower than values derived from fits to measured particle ratios and transverse momentum spectra. The processes in RQMD to which the differences can be attributed to are the non-ideal expansion of the hadronic matter and the absence of chemical equilibrium at freeze-out.

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The dynamical evolution in ultrarelativistic nucleus-nucleus collisions proceeds in three stages. The initial phase is characterized by mutual interpenetration of the two nuclei which destroys the coherence of ingoing nuclear wave functions and leads to production of secondary quanta. In the second stage, entropy generation slows down, because the system evolves hydrodynamically, i.e. in or near to local kinetic equilibrium. The system may be characterized as a hadronic gas or as a quark-gluon plasma which later undergoes a phase transition back into the hadronic world. Which state is realized, depends on the initial conditions, most importantly the energy and baryon density. Hydrodynamic expansion cools and dilutes the system up to densities at which the hadrons cease to interact (freeze-out). Afterwards they stream out freely and reach the detectors. The extraction of the phase diagram and other bulk properties using penetrating probes like photons or hadronic final-state observables becomes much easier if the system evolves dominantly according to hydrodynamical equations of motions. There is probably no doubt that the conditions of hydrodynamical evolution can be met during a part of the evolution, if the energies of the colliding nuclei are sufficiently high. However, it is worthwhile to study whether hydrodynamical behaviour is exhibited in AA collisions at presently available energies (up to 200 AGeV at CERN-SPS). The hydrodynamical model [1] has been widely used to describe nucleus-nucleus collisions in this energy domain [2]-[7]. In particular, it was suggested that the final hadron momentum spectra could be understood as a convolution of hydrodynamic motion (collective flow) and a stochastic component determined by the freeze-out temperature [8]. Subsequently, available experimental data from AA collisions at AGS (energy 10-15 AGeV) and at CERN have been interpreted based on these assumptions (see e.g. [5],[9],[10]). However, for a satisfactory understanding of the experimental results it is important to assess how large the corrections to the hydrodynamical picture are.

How non-ideal is the hydrodynamics of expanding hadronic matter which is created in nuclear collisions at CERN energy? The role of transport coefficients in a thermal hadron gas which describe the ‘restoring forces’ in case of infinitesimal deviations from equilibrium has already been discussed [11],[12]. Here, I use a semi-classical transport theoretical approach (Relativistic Quantum Molecular Dynamics) to study the deviations from hadronic fluid dy-

namics. The advantage of a transport calculation is that it is not restricted to situations close to equilibrium. In addition to assuming a common flow velocity, ‘model-independent’ analysis of collective and stochastic component by an analysis of experimental momentum spectra or correlation functions have relied on the concept of a thermal state at freeze-out. However, the assumption of an abrupt transition from a system which maintains local equilibrium into a gas of free hadrons is a drastic idealization. In a hydrodynamic description, corrections associated with heat conduction and viscosity would start to play a significant role before freeze-out. Is an analysis of the hydrodynamic flow effect on the hadron momentum spectra jeopardized by the break-down of hydrodynamics in the dilute stage of matter evolution? In order to address this question hadron distributions in seven-dimensional phase space calculated using the RQMD model were carefully studied. The results of the analysis to be presented will be restricted to two systems, central Pb(160A GeV) on Pb and S(200A GeV) on S collisions. Comparisons between the two will allow us to estimate the influence of finite mass number and size on the hydrodynamical behaviour. Here, the focus will be on an analysis of the transverse degrees of freedom, because the expansion in the longitudinal direction is dominated by transparency effects as in the Bjorken scenario [13].

The processes which occur in the initial stages before hadronization are outside the scope of this Letter. In the present context, these processes merely serve to set appropriate initial conditions for the evolution of the hadronic matter. Therefore, I give only a short resume of the physics at this stage which is incorporated in the transport approach RQMD (see Ref. [14] for an extensive description). The soft – nonperturbative – regime of strong interactions has been modeled in RQMD as the excitation and decay of longitudinally stretched color strings, which can be viewed as an idealization of chromoelectric flux tubes. Flux tubes generated in central high energetic nucleus-nucleus collisions can be in higher dimensional charge representations of color SU_3 , because the effective color charge per unit transverse area may exceed unity, the so-called color rope formation or string fusion. I note that the transverse momentum generated from rope fragmentation is not much larger than in independent string fragmentation, its difference being clearly smaller than the additional transverse momentum which is gener-

ated after hadronization in the evolution of the hadronic resonance matter. Furthermore, the initially produced transverse momenta of particles in the central region are oriented randomly. The collective flow in transverse directions starts at velocity zero, in contrast to flow in the beam direction. The hadronization time is approximately given by 1 fm/c in S+S and 2 fm/c in Pb+Pb (the latter being larger due to the nonnegligible finite size effects related to the Lorentz contraction of the ingoing nuclei).

After hadronization, the hadrons formed are propagated on classical trajectories and may interact with each other via binary collisions. Mean field effects, although built into the RQMD model as an option for baryon propagation, are neglected throughout this paper. Most of their effects in a dilute meson fluid tend to cancel, because their contribution has a different sign above and below the energy of a resonance pole as noted in Ref. [15]. The most striking feature of hadron-hadron interactions at low and intermediate energies, which are relevant after hadronization, is the formation of resonances. These processes are described by adding Breit-Wigner type transition rates (see Ref. [14] for details). Great care has been exercised to respect detailed balance constraints arising from time-reversal invariance, in particular with resonances ingoing into collisions. Only then equilibration studies like the one presented here become meaningful.

Let us turn now to an analysis of the space-time evolution of the hadronic source as generated by the RQMD model. Fig. 1 displays the calculated average ‘temperature’ T in central Pb(160A GeV) on Pb and S(200A GeV) on S collisions as a function of the boost invariant parameter $\tau = \sqrt{t^2 - z^2}$, with z the coordinate along the beam axis and $(t, z) = (0, 0)$ defined as the touching point of the two impinging nuclei. T is defined here locally by the ratio between the average of the two transverse diagonal components of the hadronic energy-momentum tensor and the density of all hadrons, both quantities taken in the rest system of the fluid. The stress tensor has the standard form given from kinetic theory

$$\Theta^{\mu\nu} = \sum_h \int \frac{d^3p}{p^0} p^\mu p^\nu f_h(x, p) \quad , \quad (1)$$

with $f_h(x, p)$ denoting the one-particle phase space distribution. The sum in eq. (1) runs over all hadron species h . The spatial average of T in a hypersurface of constant volume (chosen as $\pi R_A^2 \cdot 1 \text{ fm}$) with largest local energy

density is calculated at fixed τ . Of course, in equilibrium, T just gives the temperature of the system. The initial strong increase of T with τ up to 4 (2) fm/c in Pb+Pb (S+S) reflects the preequilibrium stage which is a relic of the flux tube dynamics. It does not imply that a relevant amount of transverse momentum per hadron is created in this stage. The reason for the initially depleted transverse T values is that the longitudinal hadron momenta which enter into the energy denominator of eq. (1) start out with an extremely hard distribution. The values of T_z defined by employing the longitudinal component of the stress tensor Θ^{zz} show a spike as a function of τ with maxima on the order of 1 GeV (cf. fig. 1). Ingoing nucleons which have not collided yet are excluded in calculating the stress tensor and hadron densities. In terms of an effective equation of state the transverse pressure P is ‘ultra-soft’ as a function of energy density ϵ , the effective ‘bag constant’ defined by $(\epsilon-3P)/4$ well in excess of $(200 \text{ MeV})^4$ at this stage. The maxima of the function $T(\tau)$ close to 4 (2) fm/c are reached at a time when the longitudinal T values approach the corresponding transverse values, and the local momentum distributions become isotropic. Only after this has happened can local equilibrium be achieved, and a hydrodynamic concept will give equivalent results. Both in Pb+Pb and in S+S, the system stays at a temperature near 140-130 MeV for about 2 fm/c. The temperature range found from the calculations can be considered as an a posteriori justification of the approach taken in RQMD which combines 1+1 dimensional prehadronic (flux tube) dynamics with the resonance gas picture for the hadronic stage. It is expected that a system with temperatures of this order can be reasonably well described in terms of hadronic degrees of freedom [16].

After some time, T starts to drop continuously in Pb+Pb (S+S) reactions, far below values usually assumed for the freeze-out temperature in hydrodynamical calculations which are based on mean free path arguments [16]. Indeed, the strong drop seen in the RQMD calculation is related to the onset of hadronic freeze-out. In fig. 2 the calculated spectrum of times in the C.M. frame at which hadron of different species (protons, pions and kaons) have their last interaction (collision, decay) is displayed. The maxima of these freeze-out time distributions are around 14 (5) fm/c for mesons, but the distributions are rather wide. A considerable width of the freeze-out hypersurface in the time-like direction is also found in other transport calcu-

lations (see e.g. Ref. [17] for a discussion of AA collisions at AGS energies) and may eventually be included in hydrodynamic calculations [18]. Continuous decoupling of hadrons influences the cooling process in the high energy density region as early as after 6 (4) fm/c. The calculation of the hadronic stress tensor has been repeated, artificially suppressing the free streaming after freeze-out by ‘glueing’ the hadrons to the position of their last interaction. This modified analysis can be employed to estimate the additional cooling effect due to the freely streaming component in the gas. The result for the modified T evolution is also presented in fig. 1 (shown by dots). It demonstrates that the drop of the T values with time is caused by free hadron streaming after freeze-out.

By construction, T calculated in the modified analysis has to approach a constant value after all strong interactions have ceased. One can see that T approaches 130 MeV in both reactions, if free streaming is suppressed. It is reasonable to compare this asymptotic T value to the freeze-out temperature in hydrodynamical calculations with instantaneous conversion of local fluid elements into free hadrons [19]. A freeze-out value of 130 MeV for a fireball of a few fermi size is consistent with the criterion that the collision rate should be smaller than the expansion rate in order that hydrodynamics be applicable. Applying this criterion to a baryon-free fireball the authors of Ref. [16] find a freeze-out temperature around 140 MeV and correspondingly smaller values if a positive chemical potential for pions is built up.

Some remarks are in order with respect to recent interpretations of experimental data for central S on A collisions at 200 AGeV. The temperatures which have been fitted to final particle ratios either in a hadronic gas [20, 21] or in a deconfined plasma breakup scenario [22] (however, without the contribution from gluon fragmentation) are considerably larger (in the range 160 to 230 MeV) than the freeze-out ‘temperature’ value found here. This may not be really surprising, because chemical equilibrium is expected to be lost much earlier than kinetic equilibrium [16]. The RQMD calculations support this scenario. In particular, the strong strangeness enhancement in the (anti-) baryon sector experimentally observed by the NA35 and WA85 groups [23] which calls for temperatures in excess of 160 MeV in chemical equilibrium approaches is well reproduced by RQMD [24]. From the RQMD calculations, I therefore conclude that chemical and kinetic equilibrium are

not simultaneously attained in a sizable fraction of the source.

The final hadron transverse mass spectra measured for S induced reactions exhibit an approximately exponential behaviour with rather similar inverse slope parameters (‘apparent temperature’) around 200 MeV in central S+S reactions and 230 MeV for heavy targets. Pion spectra for which concave shapes have been observed are the only exception. The Boltzmann-type spectra make it difficult to disentangle flow and temperature effects unambiguously [5, 9]. Smaller freeze-out temperatures can be traded against larger transverse flow velocities and vice versa. It was suggested in Ref. [9] that the measured spectra allow average flow velocities of at most 0.4 c in S+S collisions. ‘Circumstantial evidence’ for a freeze-out scenario with $\langle\beta_t\rangle=0.25$ c and $T=150$ MeV was presented. However, RQMD calculations whose results agree rather well with the experimental data yield even larger collective velocities. Averaged over the freeze-out hypersurface, β_t of pions in the central rapidity region ($y_{CMS}\pm 1$), amounts to 0.47 for S+S and 0.58 c for Pb+Pb. On the other hand, particles heavier than pions exhibit less flow: e.g. for protons $\beta_t=0.41$ (0.46) and for kaons $\beta_t=0.34$ (0.45) in S+S and Pb+Pb collisions respectively. The observed effect is in line with the findings in Ref. [12] that more massive hadrons than pions equilibrate slower at relevant temperatures around 150 MeV, in particular have much larger energy relaxation times. Therefore these hadrons cannot be ‘dragged’ by a fluid composed mostly of pions. As a result, particles with larger rest mass experience smaller flow velocities, but their momenta are more sensitive to the boost from flow. An analysis of the resulting momentum spectra based erroneously on the assumption of a common flow velocity will tend to overestimate the freeze-out temperature. This effect is demonstrated in fig. 3 in which the transverse mass spectra of pions, protons and kaons at central rapidity are shown together with the average transverse velocities and densities at freeze-out as a function of transverse distance (for Pb(160AGeV) on Pb). Fitting the spectra by exponentials, the pion slope parameter has a value of 230 MeV at large transverse masses $>m_0+1$ GeV/c², very similar to proton and kaon slopes. Fig. 3 also contains modified spectra for protons and kaons in which these particles get an additional transverse boost with $\Delta\beta_t=\min(\beta_{max}, (r_t/3\text{fm})\cdot\beta_{max})$ to mimic the larger flow velocity of pions ($\beta_{max}=0.2/0.15$ c for p/K). It is obvious that an interpretation of the in-

verse slope as a common temperature would become impossible, if proton and kaon distributions had the same velocity profile as the pion fluid. Transverse mass distributions of nuclear clusters like deuterons may clarify the role of collective flow in the forthcoming Pb on Pb experiments at CERN-SPS. RQMD predicts a pronounced shoulder-arm shape of the spectrum which is characteristic of collective flow [25] and is missing in S induced collisions in case of truly heavy ion reactions [26].

In summary, the hadronic phase space distributions calculated with the transport model RQMD for AA collisions at 160-200 AGeV have been analyzed. After a preequilibrium stage, the hadronic matter starts to expand into the transverse directions, with a temperature of around 140 MeV. While the pions acquire average transverse fluid velocities of up to 0.6 c , heavier particles like protons and kaons cannot keep up with the pionic fluid, having average velocities lower by about 20 to 30 %. Although kinetic equilibrium breaks down in the final dilute stage of AA collisions, the system locally resembles a thermal system at temperature 130 MeV if the free streaming of final-state hadrons is suppressed. This freeze-out temperature is consistent with estimates based on mean free paths and expansion rates in a thermal fireball but lower than values suggested in the literature which were derived from fits to measured particle ratios and transverse momentum spectra. The processes in RQMD to which the differences can be attributed to are the non-ideal expansion of the hadronic matter and the absence of chemical equilibrium at freeze-out.

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Figure Captions:

Figure 1:

Evolution of T as a function of τ : T is defined by the ratio of one of the spatial diagonal components of the hadronic stress tensor Θ^{ii} and the hadron density, both quantities evaluated in the local rest system of the hadronic matter. T is equal to the temperature for a classical ideal gas in equilibrium. The upper (lower) part of the figure displays the evolution of T employing the longitudinal (average of the transverse) component(s) of Θ^{ii} . Stress tensor components and hadron density are averaged over the region of highest local energy density with total volume $\pi R_A^2 \cdot 1$ fm in the CM frame. The RQMD (version 2.1) results for the system Pb(160 AGeV) on Pb are shown on the left, for S(200 AGeV) on S on the right hand side. Both reactions have been calculated for impact parameters less than 1 fm. The results of the default calculation are represented by histograms. Also shown is the result (dots) which has been obtained by freezing the 3-vector positions of hadrons after they have suffered their last interaction.

Figure 2:

The distribution of freeze-out times evaluated in the CM frame for different hadron species: protons (straight lines), pions (dashed lines) and neutral (anti-) kaons (dotted lines). Only particles with CM rapidity less than one are included. The RQMD results for the system Pb(160 AGeV) on Pb are shown on the left, for S(200 AGeV) on S on the right hand side. (The distributions have been renormalized to give the same integral as for the protons in Pb+Pb.)

Figure 3:

Transverse mass spectra $1/2\pi dN/m_t dm_t$ as a function of $\Delta m_t = m_t - m_0$ (top), average transverse velocity β_t (middle) and density distribution dN/dr_t (bottom) which are integrals over the freeze-out hypersurface but keeping the transverse freeze-out distance r_t fixed. The results are for protons, neutral kaons and pions $(\pi^+ + \pi^-/2)$ in a central rapidity window $(y_{CMS} \pm 1)$. The calculations have been done with RQMD for the system Pb(160 AGeV) on Pb with $b < 1$ fm. (The freeze-out density distributions of kaons and pions have been renormalized to give the same integral as for the protons.)

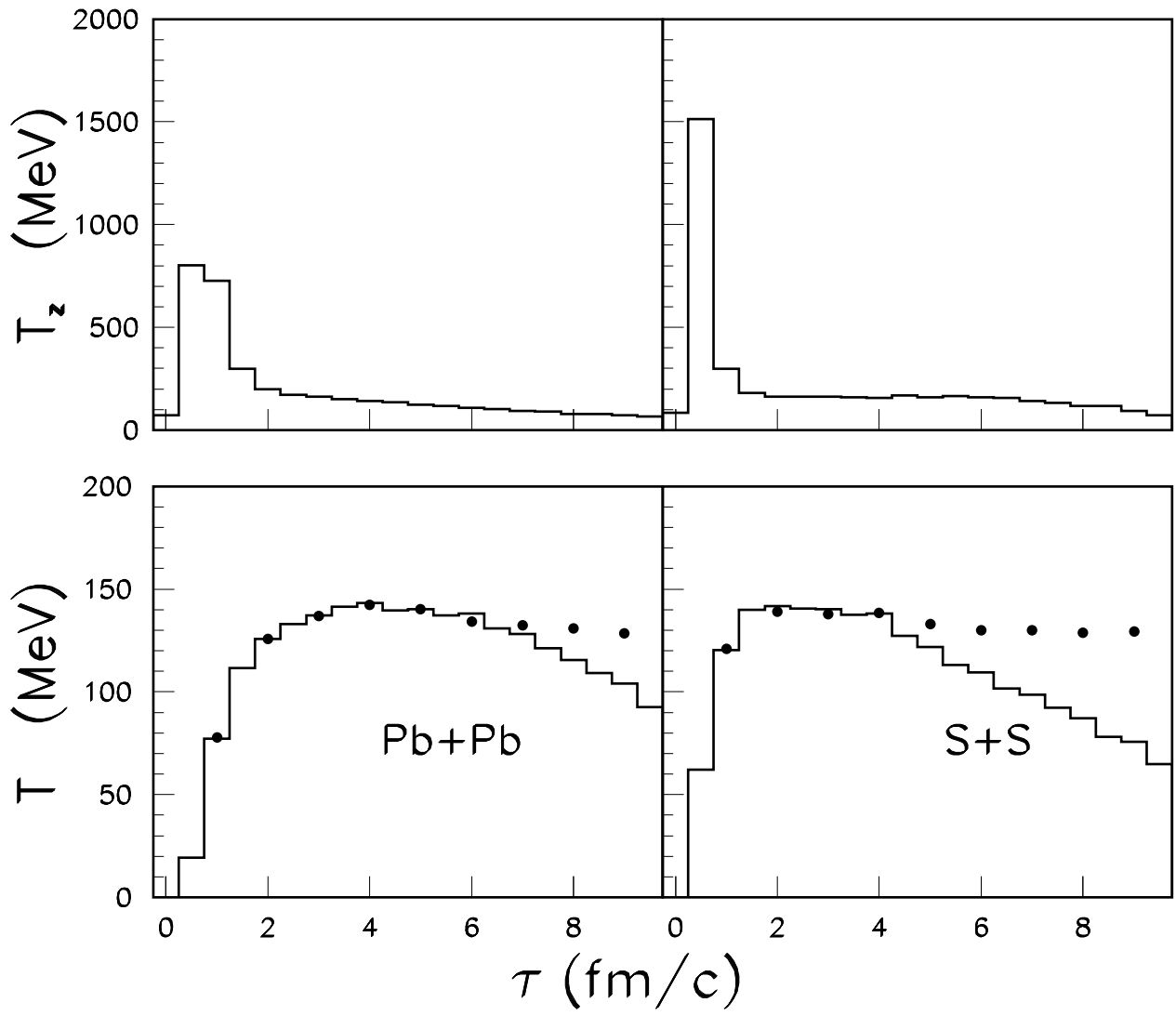


Figure 1:

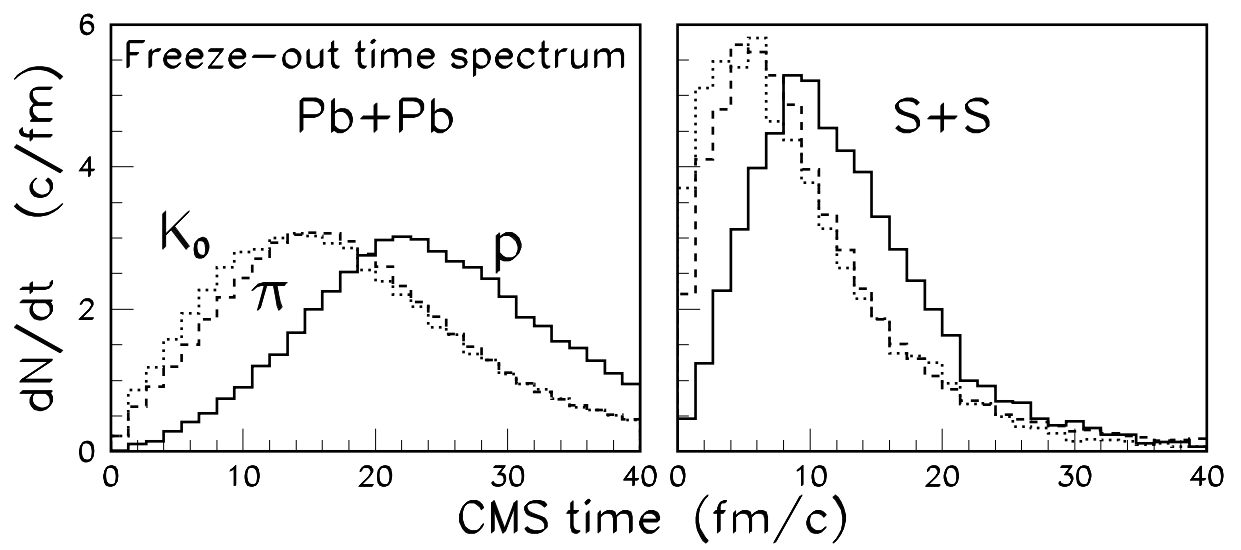


Figure 2:

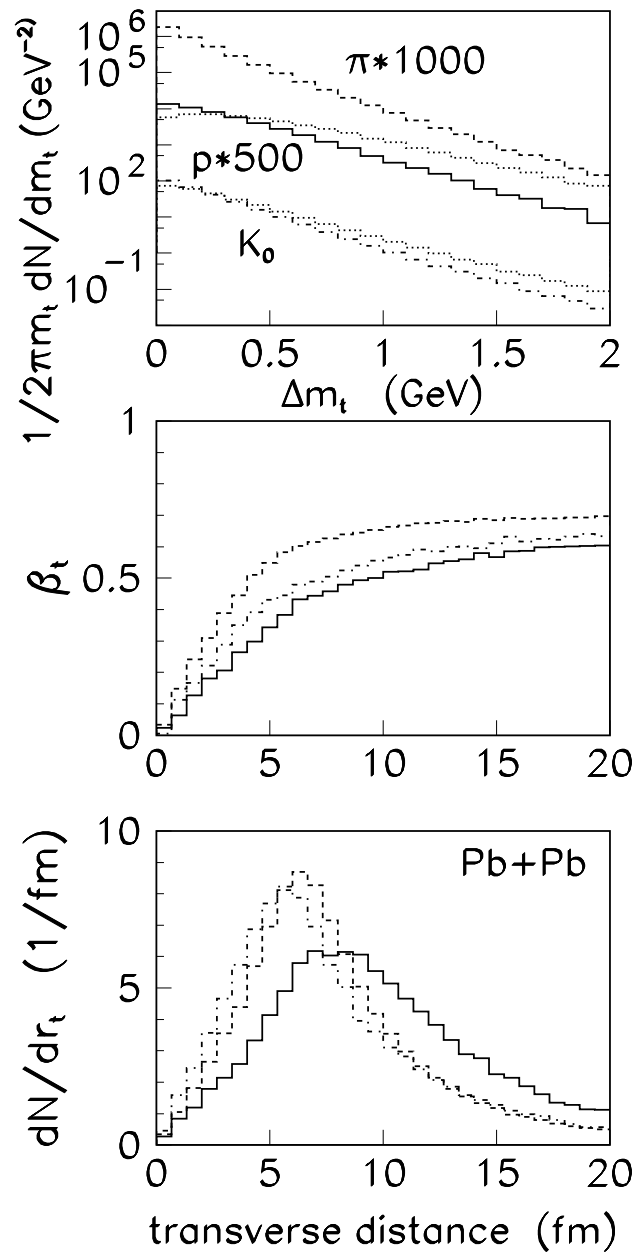


Figure 3: